GUIDELINES FOR THE QUALITY ASSURANCE OF GEOMEMBRANE LINERS FOR ENVIRONMENTAL PROTECTION

Alberta
ENVIRONMENT

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ABSTRACT

Several failures have occurred in geomembrane lined fluid impoundments in Alberta due to the lack of adequate quality assurance programs during the design, specification and installation phases of projects.

The number of geosynthetic containment systems being installed is increasing at a rapid rate and their number includes hazardous waste landfill sites. It is evident that the understanding of geosynthetic materials has still not caught up with applications technology and that more problems with installations will be experienced if adequate quality assurance programs are not established.

This report presents guidelines for a complete design-to-installation Quality Assurance program for a High Density Polyethylene geomembrane in a hazardous waste landfill site. While the details are specifically applicable to HDPE the general principles of the program are applicable to other geosynthetic materials and it should be possible to assemble appropriate quality assurance, control or verification programs for any synthetic lined system from the component parts of this program.

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INTRODUCTION

Synthetic liners are finding increasing use in Alberta for a multitude of containment applications including sewage lagoons, brine ponds, water reservoirs, hazardous waste landfills, irrigation canals, tank farms, transformers containing PCBs etc.

The purpose of their use is two-fold, to protect the environment and to contain a valuable resource. Thus, they must not leak.

Synthetic lining material, more commonly called geomembrane, although not truly 'impermeable' can have an extremely low permeability coefficient when properly selected to be compatible with the contained fluid. However, most installations are large enough that a significant amount of field seaming is required which, in northern climates, requires a great deal of experience to complete satisfactorily. Many problems have been encountered with leaking geomembrane seams but most, if not all these problems are the result of improper material selection or lack of sufficient care to ensure that the geomembrane had the specified physical properties or was seamed correctly. There is no question that both geomembranes and seaming procedures are fundamentally capable of providing the performance required of them.

To complement geomembranes other geosynthetic products are available which provide cushioning, filtration, gas venting and drainage properties far in excess of conventional natural materials such as sand and gravel. When such products are used with geomembranes to fabricate an engineered containment 'system' as many as eight layers of geosynthetics could be used in a hazardous waste landfill.

It is thus essential that such systems be correctly designed with a full knowledge of the properties of these synthetic materials and how they interact with each other. Then they must be installed with the same degree of understanding so that the long term performance of the lining system is not compromised. Unfortunately, most tests for evaluating the quality of installed liners relate to immediate properties and neglect the long term behaviour.

This report presents a set of Quality Assurance (QA) guidelines for owners of containment systems and engineers associated with their design and installation to follow to ensure that the system will perform as intended.

The guidelines have been prepared for a hazardous waste landfill where the ultimate QA program will be required. For less critical installations the appropriate inspection stages can be extracted from this report to provide the basis for a less stringent QA, Quality Control (QC) or Quality Verification (QV) program as outlined on page 4.

TYPICAL PROBLEMS

1. A containment system design using geonet to conduct leachate to a drain showed a break in the associated geotextile filter layer such that clogging of the geonet would most likely occur.

2. A geomembrane lined pond with a large surface area susceptible to wave formation did not contain a cushioning/reinforcing geotextile underneath the membrane at water level. The constant pounding of the waves caused the subgrade to slump under the membrane and the liner ultimately failed.

3. On inspection of a completed sewage lagoon lining it was found(1) that all seams peeled apart with a minimum of effort. On further examination it was found that the high density polyethylene membrane was defective and could itself be delaminated. Yet further inspection showed the membrane to contain an unacceptable filler component. This membrane should not have been allowed out of the manufacturing plant, it should not have been accepted by the installer and it certainly should not have been installed by the installer.

4. An installer ran out of the HDPE weld extrusion resin part way through a job and replaced it with raw resin containing no carbon black (for ultraviolet protection) from his local plastics supplier. After completing the seams he painted the white resin black! The seams failed by brittle cracking within 6 months. In the same installation seams were designed in a 90 degree corner - almost impossible to weld. In attempting to weld in this corner as many as 5 beads had been laid adjacent to one another thus severely overheating and embrittling the membrane. This installer was evidently unaware of the behaviour of the material with which he was dealing.

5. A consulting engineer specified that HDPE membrane be seamed by the solvent welding process. HDPE cannot be solvent welded. The same company specified that the installer be responsible for providing independant third-party inspection for his work.

6. An installer had adjusted the rollers on a hot air welder to a slightly wedged orientation to make it easier to deviate from a straight line without tearing the geomembrane. As a consequence the seam was well-fused along one edge and poorly fused along the other. The apparent 50 mm wide seam was only fused satisfactorily over 6 mm!

7. Insufficient allowance for thermal contraction in exposed liners combined with notch geometries in extruded seams caused two liners to fail at several locations after two years of service.

All these problems could have been avoided with appropriate communication and quality assurance programs.

It is essential to remember that polymeric geomembranes are not simple, forgiving materials that will tolerate abuse.

LINING MATERIALS

A previous Alberta Environment report[2] has outlined the different materials available for geomembranes, their seaming techniques and some test methods.

A U.S. National Sanitation Foundation standard, #54 entitled "Flexible Membrane Liners" lists the test methods and minimum mechanical, physical and chemical properties required by 18 of the more common geomembranes when used in lining systems.

At present, in western Canada the predominant geomembrane material used in landfills, sewage lagoons and industrial fluid impoundments is HDPE. Some chlorinated polyethylene (CPE) is used in water reservoirs but in declining amounts. Polyvinylchloride (PVC) continues to be used for irrigation canal liners in southern Alberta [3]. Very little chlorosulfonated polyethylene (CSPE) under the trade name, Hypalon, is now used.

Because of the predominance of HDPE and the relatively sophisticated nature of its seaming procedures these guidelines will be based on the specific requirements for HDPE. Similar principles will apply, nevertheless, to the other geomembranes.

Low Density Polyethylene (LDPE) is seeing increasing use as secondary containment for short periods under Arctic tank farms while Linear Low Density Polyethylene (LLDPE), which has properties similar to HDPE but is more flexible and has a wider 'window' of welding parameters is gaining more recognition. Similarly, copolymers with Ethylvinylacetate (EVA) are being evaluated in thin membrane form for use in place of PVC.

Seaming techniques are of three basic types;

- extrusion
- thermal
- adhesive

They are satisfactorily described in previously referenced publications[2,3]. The quality control test procedures used to evaluate the seams are independent of the seaming technique.

QUALITY PROGRAMS

The principles behind, and differences between Quality Assurance (QA), Quality Control (QC), Quality Verification (QV) and other quality programs are detailed in the Canadian Standards Association Z299 series of standards[4].

QA can be described as a planned and systematic pattern of all means and actions designed to provide adequate confidence that items or services meet contractual and jurisdictional requirements and will perform satisfactorily in service.

With reference to geosynthetic materials QA refers[5] to means and actions to assure conformity of the installation with the drawings and specifications.

Quality Assurance includes Quality Control.

QC can be described as those actions which provide a means to measure and regulate the characteristics of an item or service to contractural and jurisdictional requirements.

In the context of geosynthetics QC refers to those actions taken by the manufacturer, fabricator and installer to ensure that the material and workmanship meet the requirements of plans and specifications.

CAN-3 Z299 identifies the parameters which define which type of Quality program should be in place for any project. For example, it is obvious that the program for a water reservoir will not be required to be as rigorous as that for a hazardous waste landfill.

DEFINITIONS

To establish the responsibilities of the various parties involved in a geosynthetic containment installation the following definitions are available(5):

Designer - Responsible for the design, drawings, plans and specifications of the lining system and the supporting soil.
Resin Supplier - Produces and delivers polymer resin to the Manufacturer.
Manufacturer - Responsible for production of geosynthetics from resin. In the case of geomembranes, produces rolls of a constant width.
Fabricator - Responsible for the fabrication of geomembrane blankets from geomembrane rolls.
Shipper - Transports geomembrane rolls and other geosynthetics from Manufacturer to Fabricator or the site, and/or geomembrane blankets from Fabricator to the site.
Earthwork Contractor - Responsible for the preparation of the supporting soil on which the system is to be installed; may also be the party responsible for placing earth and granular materials (if any) over the installed system.
Installer - Responsible for field handling, placing, seaming and other site aspects of the geosynthetics, including geomembrane panels; may also be responsible for transportation to the site; may also be responsible for anchor trenches.
QA Contractor - Party (independent from the Designer, Manufacturer, Fabricator and Installer) responsible for observing and documenting activities related to the quality assurance of the geosynthetic liner system. The Quality Assurance Contractor is the employer of the Quality Assurance Team. The Quality Assurance Team includes at least one Quality Assurance Engineer and usually also includes a Quality Assurance Manager and several Quality Assurance Monitors.
Owner/Operator - Owns and/or is responsible for the hazardous waste landfill, i.e., the party responsible for operating the landfill.
Project Manager - The official representative of the Owner; i.e., the individual in charge of coordinating field activities.

RELATED STANDARDS

The following standards are applicable to the testing and evaluation of geomembrane installations - note that NSF #54 contains minimal specifications for geomembrane seams. It is the only national standard containing seam specifications:

ASTM D792	Specific Gravity and Density of Plastics by Displacement
ASTM D1238(E)	Flow Rates of Thermoplastics by Extrusion Plastometer
ASTM D1603	Carbon Black in Olefin Plastics
ASTM D638	Tensile Properties of Plastics
ASTM D1593	Non-rigid Vinyl Chloride Plastic Sheeting (Thickness)
ASTM D882	Tensile Properites of Thin Plastic Sheeting (Seam Shear Strength)
ASTM D413	Rubber Property - Adhesion to Flexible Substrate (Seam Peel)
NSF 54	Flexible Membrane Liners
ASTM D4437	Determining the Integrity of Field Seams used in Joining Flexible Polymeric Sheet Geomembranes 1984 Vol 04.08
CAN3 Z299 M1985	Quality Assurance Program

The National Sanitation Foundation has recently started certifying specific products as meeting their standard specifications.

DESIGN

The QA program should be initiated at the design stage by submitting drawings for independent third party inspection or, at the very least, to arms-length peer review. The reviewer should have considerable experience in the installation of geosynthetic systems and particularly geosynthetic materials engineering. The reviewer will ideally be the third party QA contractor hired for the installation phase of the project.

The parameters which should be examined include the following:

- Geomembrane thickness - with respect to contained load, coarseness of subgrade and cover materials, probability of penetrating stresses, potential for animal interaction, action of ice and waves, etc.

- Seamability - seaming thin geomembranes (less than 0.75 mm) and seaming thicker membranes to thinner membranes may present some difficulties.

- Seam geometry - ensure no problems develop from mechanical attachment of ice etc.

- Need for geotextile - to provide venting for gases produced under the membrane, to provide cushioning for coarse subgrade and cover, to provide cushioning for ice impact, to prevent subgrade from slumping from repeated ice and wave impact.

- Subdrains - does geotextile filter provide a continuous barrier between solids and drainage course to prevent clogging of drainage course? Are there sufficient layers of drainage net to accommodate expected leachate or leakage flows? Will geotextile perform adequately when the installation is filled? Are geotextile and geonet mechanically compatible when the installation is filled?

- De-watering - is there a sump to deal with rainwater during installation?

- Side slopes - with respect to friction factors between various layers of the lining system.

- Anchor trench - with respect to depth, width and fill.

- Membrane material - is it compatible with the contents of the installation? Is a chemical compatibility test, such as EPA 9090[6], required?

- Penetrations - is membrane correctly attached to the penetration? Are specifications for concrete pads adequate?

- Panel layout - are number of field seams minimized and are panels correctly oriented on side slopes?

- Contraction allowance - ensure that minimum expected service temperatures are identified to define the correct thermal contraction allowance between fixed points, especially for exposed membranes.

- Safety - is there a means of climbing up the side slopes out of fluid impoundments?

- Surface wear - are abrasion resistant coverings appropriate for cables, slurry inlets, vehicular access etc.?

- Gas venting - with respect to design, number and location of vents.

GEOMEMBRANE MATERIAL

The material should not be specified to be "... product ABC or equivalent." since it is impossible to define equivalence. The different manufacturers produce sheet in different widths, with different mechanical properties joined together with different seaming techniques.

The geomembrane will normally be ordered to meet both the specifications within NSF standard #54 and the minimum specifications presented by the manufacturer for his own sheet. It is expected that the manufacturer's specifications will exceed those required by NSF #54.

While it is normally specified that membrane be produced from "first quality, prime material" it is not unusual for manufacturers to use rework material trimmed from the edge of manufactured geomembrane. There are two alternative approaches to take;

- Specify quite clearly that reworked material shall not be used to manufacture geomembrane, or;

- Specify that rework material may be used but only with the direct permission of the purchaser.

Several conditions must be imposed if reworked material is to be allowed and, in fact, there is no reason why reworked material should not be allowed - the natural gas distribution industry has permitted the use of rework material for several years;

> Rework material should only be used by itself to produce membrane. It should not be mixed with virgin material. Rework material should not have been stored outdoors and it must be clean and dry. The membrane producing the reworked material must not have been rejected due to failure of tests indicating poor resin quality. Previously reworked material should not be used. Sampling to measure density and melt index of the rework feed material must be frequent. Finally, sheet produced with reworked material must be clearly identified.

It is necessary that the resin provided for extrusion welding have the same melt index as the membrane material and thus it is normally specified that the welding resin be the same as the membrane resin. This ensures that when the weld extrudate and the membrane are at the same high temperature they have the same "fluidity" and can intermix homogeneously.

Care should be taken that if welding rod is used it be free of voids.

When reviewing proposals from the various manufacturers it should be remembered that there are many different grades of HDPE, just as there are many different 'steels', and that there can be significant differences in properties. Geomembranes are manufactured in widths from 2 to 10 m by different techniques and thus some products require five times the number of seams than others. Seaming techniques produce seams of different geometries which thus behave differently in service.

Supporting information should thus be requested with installation proposals.

PROPOSALS

To ensure that a meaningful comparison can be made between the various products and installation techniques the following information should be requested with all proposals;

- geomembrane specifications and properties, including test methods.
- proposed panel layout plan.
- examples of QC certificates.
- types of welding equipment used.
- number of machines planned for this project.
- number of experienced personnel scheduled for this project and their responsibilities.
- resumes of personnel.
- number of local labourers to be hired.
- amount of back-up equipment to be on-site.
- details of QC program and test equipment used.
- list of five previous similar projects and contact person for reference purposes.
- standard warranty details.
- assurance that specifications and acceptance criteria for the project can be met.
- the 'window' of ambient conditions within which seaming can be satisfactorily performed.

CERTIFICATES

Prior to shipping any geomembrane from the manufacturing plant mill certificates should be obtained and reviewed to ensure that the material is as-specified. Such certificates will be required even if actual mill inspections are being performed by an independent QA contractor.

A copy of the raw resin supplier's certificate will indicate that the base resin is satisfactory. This will normally be supported by the results of audit testing performed by the membrane manufacturer when he receives the resin.

The manufacturer's certificate to confirm the quality of his product should, at a minimum, include the following;

- the resin lot number from which geomembrane was made.
- density of the membrane to ensure it is not significantly different from the base resin.
- melt index.
- tensile yield strength.
- elongation at yield.
- elongation at break. Note that strength at break is not considered meaningful.
- carbon black content.

These tests, apart from carbon black content and perhaps melt index should be performed on each roll of material.

Certification or documentation must be provided for each roll showing;

- roll numbers and blanket numbers if several rolls are seamed together prior to site delivery.
- date of manufacture and date of plant seaming.
- thickness and length.
- the location and type of all flaws.

Note that flaws can be repaired while defects are rejectable items. It must be recognized that it is impractical to reject long lengths of expensive geomembrane simply because they contain a few flaws which can be repaired. However, the number of flaws must not be so great that the quality of workmanship can be questioned. It is not unreasonable that the number of flaws be required not to exceed one per 500 square metres of membrane surface - one side only.

Dependent upon the welding technique to be used the acceptability of edge flaws should be defined. They must not interfere with the seaming process.

For large orders or for membrane in critical applications mill inspection by the QA contractor is appropriate. The inspector should be given at least 48 hours notice when production is to commence and be provided with lockable desk facilities and access to all areas of the plant involved with evaluating the quality of the membrane. In turn, he must respect the proprietary areas of the plant which may include the manufacturing equipment itself.

He will visually inspect the product, monitor test procedures and approve test certificates if required. He may perform simple audit tests himself such as measuring membrane thickness. He will monitor loading procedures for shipping and sign-off the loading inspection report. He will prepare daily inspection reports and submit them to the owner of the membrane.

TRANSPORTATION

It is essential that geomembrane be prepared correctly for shipping and documentation produced to prove that it was loaded without damage and satisfactorily to both manufacturer and transporter. This will eliminate 'buck-passing' if it is damaged on arrival at site.

The membrane rolls should be strapped in such a way that no damage occurs to the outer wraps on each roll and such that the straps do not damage adjacent rolls.

Rolls should be supported such that no penetrating stresses are induced in the membrane and they should not be allowed to move during transportation.

Although not presently done it would be advisable to require that rolls be shipped with end caps in place to completely protect the edges of the membrane. Many rolls are shipped when the inner turns have spiralled outwards thus exposing edges to potential damage which could be a major problem on seaming. End caps would help prevent misalignment of roll edges.

Each roll should be completely covered with its own wrapping or shipped with others in a closed container to prevent contamination.

The number of each roll should be visible during transportation for inspection purposes.

All rolls should be inspected on delivery to the site, if possible, before unloading.

HANDLING AND STORAGE

All materials should be unloaded at a location on the site where only one more handling step is required to take each roll to its position for laying out.

Handling should be done in such a way that no contact is made with the membrane itself unless wide, clean fabric slings are used.

Rolls should be stored on smooth, flat surfaces and covered.

If mill inspections were not performed during the manufacturing stage samples should be removed from several rolls and audit tests performed as follows;

- density.
- melt index.
- tensile yield strength.
- elongation at yield.
- elongation at break.
- thickness.

WELD PROCEDURE QUALIFICATION

Shortly after material is delivered, test welds should be made on the delivered membrane by welders scheduled to work on the project using welding equipment also scheduled for the project. A sample of each type of weld to be used should be made. It is essential that a sample of extrusion seam typical of patch and repair work be evaluated since such detail work has been shown to produce most problems during installation.

All samples should be tested in peel and shear according to the procedures and acceptance criteria detailed on pages 19 and 21.

In addition, the microstructure of the fusion and weld zones should be examined on thin slice microtome sections using a transmitted light microscope with crossed polarizing filters. Such an examination will reveal the homogeneity of the fusion zone, the degree of fusion, the presence of void defects or foreign matter and the existence of residual stresses. Such information can be used to assess the long term behaviour of the seams which is not normally reflected in the conventional shear and peel tests.

PRE-INSTALLATION SITE MEETING

After the weld procedure has been qualified and when the subgrade has been prepared to receive geosynthetic material a site meeting should be held and attended, at a minimum, by the installer, the installer's supervisor, the QA engineer and on-site manager, the general contractor, the project engineer and the owner. The purpose of the meeting is as follows;

- to review the panel layout schedule and the panel and seam numbering systems.
- to review inspection, QC sampling and testing procedures.
- to confirm that all test criteria are acceptable.
- to review seaming and repair procedures.
- to review responsibilities of each party and channels of communication.
- to review reporting procedures.
- to review schedules.
- to survey the prepared subgrade and penetrations for acceptance by the geomembrane installer. Such acceptance should be documented.

The decisions of the meeting should be documented and such minutes signed and approved by all participants. Copies of the minutes should be retained on site by the project engineer and the QA contractor.

FIELD QUALITY ASSURANCE MONITORING

It has become evident from the number of problems encountered and general experience gained while in the field that continuous on site QA monitoring is beneficial and economically viable. This inspection should be provided by the independent third-party QA contractor.

The number of QA monitors assigned to the project will depend on the number of welding machines used, the number of geosynthetic layers being installed in the containment system and the extent of testing being performed by the contractor. The QA monitors will be supervised by a QA manager.

It has been common practice until recently for the QA contractor simply to observe the test weld mechanical tests being performed by the installer at the beginning of each shift. However, some owners are now requiring that QA monitors actually perform these tests and authorize production seaming when these tests are satisfactory. If there are many machines on a large project this could significantly affect the number of QA monitors required for the project.

The QA contractor should be capable of performing his own field mechanical tests and nondestructive inspections in addition to visual inspections. He should have access to laboratory test facilities which can provide turnaround times of a few hours.

GEOMEMBRANE DEPLOYMENT

As the membrane is being unrolled both surfaces should be inspected for identified flaws and other non-identified damage. All flaws and defects should be documented and marked for repair.

The subgrade surface should be maintained in a smooth compact condition and all objects removed which may apply point stresses on the underside of the geomembrane. Similarly, no objects should be used on the top surface of the membrane which will mark or gouge it. This applies to footwear, cigarettes, hot air guns which may be left on pointing down at the membrane, excess welding extrudate, tools etc.

Adjacent rolls should be overlapped sufficiently so that on completion of seaming there is a loose flap of material on the underside of the seam about 50 mm wide to facilitate peel testing. Some manufacturers will paint a line about 150 mm away from, and parallel to the edge of the membrane to aid with the amount of overlap and alignment of adjacent rolls.

Deployment should incorporate sufficient slackness to account for thermal contraction at the lowest operating temperatures. This is particularly important for exposed membranes. At the lowest operating temperatures the membrane should just be taut. The required allowance between any two fixed points can be calculated from;

$$\text{allowance} = \gamma \cdot (T - T1) \cdot D$$

where;

γ = coefficient of linear thermal expansion, °C^{-1}
T = temperature at which allowance is measured, °C
T1 = lowest service temperature expected, °C
D = distance between fixed points.

For HDPE to be left exposed the allowance is approximately 1m per 100m, or 1%.

The allowance should be evenly distributed between the two fixed points.

The membrane should be deployed so that it goes all the way down the side and across the bottom of the peripheral anchor trench and there should be no sharp projections along the inner edge of the trench which may penetrate the membrane. Seams should be properly completed right to the edge of the membrane in the anchor trenches.

Only material which is to be immediately welded should be deployed and all free edges should be weighted down with sand bags. Wind can be a major problem during membrane installation and it is advisable to key material into the anchor trenches as soon as possible. The airfoil effect of wind blowing across the top of an excavation can very easily lift the membrane and blow it away.

Since it is somewhat inconvenient to seam membrane on side slopes it is common practice to weld the appropriate size of membrane on a flat surface and then to drag it down the slope. If this is done care should be taken that there are no sharp edges over which the membrane is dragged and seaming should be done so that loose flaps on the underside of the membrane are trailing during movement of the membrane. For hazardous waste and toxic chemical liners it is preferable to seam the membrane in-situ on the side slopes to eliminate all chances of gouges being formed on the underside of the liner which may ultimately initiate brittle fractures at these stress concentrating geometries.

SEAMING

Although seaming procedures may be somewhat proprietary or standard equipment modified by individual installers there are several key procedures which must be observed by them all in order to produce satisfactory seams. The QA monitors must be familiar with them.

It is essential that all moisture be kept away from surfaces to be welded and materials to be used in welding. All resin containers must have covers which are kept in place at all times except when resin is being transferred or replenished. All membrane surfaces must be dry for welding and subgrade sand should also be dry. If the sand is not dry a plywood board can be slid along underneath the seam as it is being welded to separate the moisture from the heat source.

In fillet extrusion welds, when the extrudate is deposited over the edge of the overlapping sheet, the top edge of the overlapping sheet should be bevelled to minimize residual stresses and facilitate welding to the edge of the top sheet.

Several installers do not consider it necessary to abrade the surfaces of the membrane where fusion is to occur or weld deposit is to be laid down. However, there is no question that better seam strengths, as measured by the peel test, result if surfaces are abraded to remove surface contamination, oxidized surface material and to expose fresh material for welding. Seaming should be done within 30 minutes of surface abrasion or else the surface should be re-prepared. This is similar to the procedure in butt-fusing HDPE gas pipe when prepared surfaces are required to be fused within 15 minutes or else they should be re-faced.

To minimize potential problems with stress concentrating surface geometries it should be required that all abrasion marks run normal to the direction of the seam and that they be no more than 10% of the thickness of the membrane deep.

Abrasion debris should be blown off the prepared surface away from the weld extrudate. Even though the debris is PE, if it is blown into the seam as it is being formed it can produce low peel strengths.

If the installer does not abrade the membrane surface it should, at the very least, be wiped clean. Thus, clean cloths must be used. Low peel strengths will again result if marginally dirty cloths spread dirt around rather than remove it.

The object of seaming is to allow the mixed molten materials to go through a thermal cycle which permits the development of a crystalline microstructure across the weld zone identical to that which exists in the parent membrane. Any ambient conditions which interfere with this time/temperature relationship will produce inferior weld strengths. Thus if it is windy or cold it may be necessary to construct barriers or shelters to bring ambient conditions in the weld area back within the acceptable 'window'.

The finished seam should have a smooth surface profile with no wrinkles, creases, notches or other severe geometrical features. Seams should be visually uniform from one edge to the other and along their length.

Each seam should be numbered and the membrane, adjacent to the seam, should be marked with the initials of the welder, the number of the machine used to make the weld and the date of welding. The membrane should be marked where any of these parameters change.

It is not unusual for seaming crews to work a night shift since geomembrane temperatures in sunlight can reach 80°C or more making the membrane difficult to seam satisfactorily. In addition, when welding is performed at night the sheet will be in its most contracted form and less contraction allowance will be required to be built in. Similarly, when cover is being spread on the liner, if it is done during the night shift the waves in the liner will not be so severe and are less likely to fold over under the cover.

WELDER QUALIFICATION

Prior to the start of production welding during each shift, it should be required that each welder/machine combination prepare test seams about 1m long for peel and shear testing. Only when satisfactory seams have been made will production welding be permitted and then only with the machine settings that produced the satisfactory test seam. If the machine is shut down, if operators change or if there are major changes in ambient conditions further qualifying test strips should be made. This testing should be a routine procedure for the welding crew.

The qualification welds should be tested according to the procedures and criteria outlined on page 19 and 21.

SEAM QUALITY CONTROL TESTING.

In addition to visual inspection there are six common ways to evaluate seam integrity;

Vacuum box testing - A long box, open on one side is laid over a section of seam coated with a soap and water solution. A vacuum is pulled on the box and the seam viewed through a window on the top edge of the box. Leaks will be located by the formation of bubbles in the soap solution. The box is moved along the seam and the test repeated.

The test is very time-consuming and will not detect defects within the seam which do not penetrate right through the seam. It is, however, probably the best test for evaluating seam intersections.

Air pressure testing - Thermal fusion seams predominantly have a parallel track geometry with a channel between the two fused tracks. The channel can be pressurized with air through a hypodermic-type needle and any pressure-loss will indicate a leak. The leak may be located audibly or by testing shorter lengths of seam. This test will also only detect defects which completely penetrate one, or both of the fusion tracks.

Air lance testing - A high pressure jet of air is directed at the edge of the seam in an attempt to force it apart. This will only occur if there is already a crevice at the edge of the seam and/or if there is an area of poor fusion right at the edge of the seam. Again it will not detect defects which are not exposed to the outer edge of the seam.

Point stress test - This qualitative test is specified in ASTM D4437 and involves pressing a blunt instrument into the edge of the seam and trying to pry it apart. It is a common test but can be strikingly ineffective. Seams which have successfully passed point stress tests have peeled completely apart when 25 mm wide strip specimens cut from the tested location have been properly tested in peel.

Ultrasonic testing - This is presently the only nondestructive technique which is capable of detecting defects completely within the seam although it does not lend itself to all seam geometries. For conventional ultrasonic techniques the seam surface must be flat, thus, extrusion fillet seams cannot be inspected. However, recent developments[7,8] using multi-frequency ultrasonic signals transmitted in to the geomembrane and received from it with separate roller probes which do not contact the seam itself have been shown to be extremely sensitive. This new technique is capable of detecting cold fusions while conventional ultrasonics is not. Cold fusion occurs when interface gaps are eliminated but the full crystalline microstructure is not permitted to develop within the weld zone thus producing a weak fusion.

This dry-scan ultrasonic technique will be particularly useful in defining those seam areas which should perhaps be cut out for destructive mechanical testing.

Mechanical testing - Peel and tensile shear tests are the most common tests for evaluating seam quality. Strip specimens 25mm wide are pulled in a tensile testing machine at a constant crosshead speed of 50mm/min according to the procedures in NSF standard #54, Fig. 1.

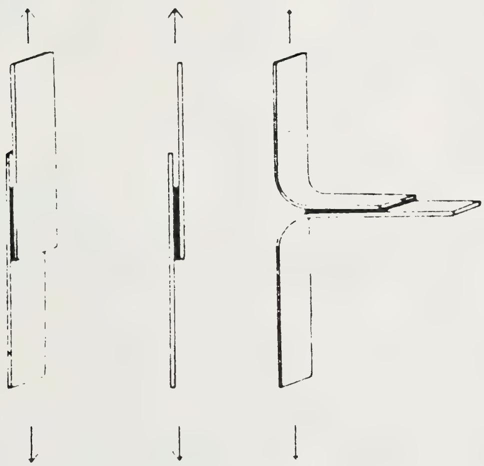

Figure 1
Orientation of specimens for
tensile shear and peel testing

The tensile shear test reproduces the obvious membrane stresses in service and conventional thought is that the seam should at least have the strength of the membrane itself.

The peel test is not intended to reproduce service stresses but is solely performed to evaluate the degree of fusion. Peel specimens should not separate along the seam but should fail in the membrane adjacent to the edge of the seam.

The peel test is conventionally performed at the underside, unexposed edge of the seam. However, the uniformity of fusion across the seam can be better evaluated by also performing a "back-peel" test at the exposed edge of the seam. It may be necessary to initiate separation so that the specimen can be inserted in the jaws of the tensile machine but this will not present a problem. A similar approach should be taken with parallel track thermal fusions where an acceptable conventional peel test will only evaluate fusion strength in one of the tracks.

According to NSF, ASTM and other proprietary standards, five peel and five shear specimens should be tested from each seam cut-out sample. Also, according to these standards, testing should be done in a controlled environment at $23 \pm 2°C$ and $50 \pm 5\%$ Relative Humidity after specimens have been conditioned in the same atmosphere for a minimum of 40 hours.

For QC tests during field installations this is an excessive length of time considering the fact that specimens may even have to be shipped some distance from the site to a laboratory. Consequently testing may be done with portable field tensile testers with all the correct parameters except the environmental control. However, if specimens do give rejectable results in the field they should be re-tested under the correct environmental conditions before a significant part of an installation is rejected. The lab tests will be the ones on which a controlling decision should be based.

When samples are cut out of field seams they should be cut with rounded corners and so that no cuts are started into the remainder of the membrane. Such cuts are effectively cracks which may propagate during service. The sample holes should be patched at the earliest opportunity.

The frequency of cut-outs is dependent upon the criticality of the installation, the area being seamed by each method and the quality of the seams being produced. ASTM D4437 suggests that samples be taken approximately every 500m of seam but other proprietary specifications(9) suggest 100 to 300m. Samples have been taken as frequently as each 15m in some critical applications. However, in taking cut-out samples one should remember that patches have to be put in their place and detail extrusion seaming is generally inferior to flat production seaming. A compromise must be reached where most of the emphasis is placed on more frequent testing strips. Nevertheless, some samples must be removed from production seams for evaluation. On average, for non-critical installations it is probably appropriate to take samples each 500m on large installations, decreasing the frequency for large flat surfaces and increasing it for slope and detail seam welding. For more critical installations, average one sample each 200m but sampling each 100m on slope and detail seams and each 300m on flat surfaces. On small installations it would be appropriate to take one cut-out sample per seam.

There are no rigid rules for sampling frequency and much will depend on the performance of the welders on the project. Unfortunately, a larger number of samples would be required to monitor poor seaming performance but then there are more patches for the less qualified welders to repair with an inferior technique! It is a Catch 22 situation which must be obviated at the beginning of the project by qualifying the installer and minimizing the number of field seams to be made.

TEST ACCEPTANCE CRITERIA.

Vacuum Box Testing. All indicated leaks must be repaired.

Air Pressure Testing. All leaks must be repaired.

Air Lance Testing. All seams which are raised must be repaired.

Ultrasonic Testing. Acceptance and rejection criteria must be defined by the QA contractor in consultation with the owner of the specific installation. The major obstacle to presenting general acceptance criteria is that there is no consensus on critical defect sizes in geomembrane seams.

A general approach with the dry-scan technique would be to require that calibration be performed on the parent geomembrane and to adjust this 'acceptable' signal to full scale height. The probes would then be moved to straddle the seam and the gain increased slightly to account for the larger volume of material between the probes. Any area of the seam which then produces a signal below a defined percentage of full scale height would then be rejectable or selected for mechanical peel and shear testing.

The strength of the ultrasonic technique is that it can be performed on 100% of the seam length produced.

Mechanical Testing Here again the actual acceptance criteria will be dependent upon the installation, the materials and the seaming system employed. A general approach can, however, be defined.

Peel and shear specimens from adjacent positions should be tested in pairs and the results used to define acceptance of one peel/shear specimen pair. The following parameters should be recorded:

Shear strength - this will rarely be less than the minimum yield strength of the parent geomembrane even if the peel specimen demonstrates complete peel separation. The result can largely be ignored.

Shear elongation - this is far more indicative of seam quality as it reflects damage done to the parent membrane by the introduction of the seam. The shear specimen must not fail at low elongation values indicative of embrittlement or stress concentrating geometries caused by seaming.

Peel separation - it is quite obvious that 100% peel separation is not acceptable but that zero separation and failure of the membrane is acceptable. It must be determined where the transition lies - is 30% separation followed by membrane failure acceptable or is 70% the maximum tolerable peel separation? There is evidence to suggest that no separation should occur since crazing damage can be induced in separated surfaces which could ultimately open up to produce brittle fractures. Seams with no peel separation can readily be prepared. In practice, maximum peel separations of 10 and 20% have been specified and such figures should apply to both conventional and back peel tests.

Peel strength - due to the complicated stress situation occurring in the peel test, specimens generally fail with little elongation and at equivalent stresses (load/cross-sectional area) less than the tensile yield strength of the parent geomembrane. As in the shear test the minimum acceptable peel strength is defined to suit the circumstances.

Thus, each peel/shear pair has four parameters to be determined. A failure in any one of these parameters will result in a failure of the specimen pair.

If one or more of the peel/shear pairs fail the complete cut-out sample should be considered not acceptable. However, if only one pair fails because peel strength is marginally low while both specimens adjacent to it are acceptable the cut-out could be considered acceptable. In this case the problem is most likely to be a minor, isolated flaw.

If the cut-out sample is rejected an additional sample should be cut out from each side of the rejected one to determine how far the defect extends.

REPAIRS

All repairs and patches should be made at the earliest opportunity to minimize the possibility of them becoming enlarged. This is particularly important with cut-out holes which are vulnerable to damage if wind gets underneath the membrane. The membrane should be weighted down at cut-outs until repairs are made.

All patches should have rounded corners to facilitate continuous, unhesitating extrusion welding. All patches should be of the same material as the parent geomembrane.

It is advisable to patch all through-thickness defects while narrow surface defects such as scratches and gouges can simply be extruded. However, no more than two extrusion beads should be laid together at any one location.

If an extruded bead is found to produce an inferior seam it may be ground down and re-extruded just once. If the attempted repair is unsuccessful a patch must be applied.

OTHER GEOSYNTHETIC MATERIALS

The QA programs for related geosynthetic materials which may be included in the lining system such as geonets, geotextiles and geogrids are logical extensions of the program for geomembranes. However, there is a difference in the approach since these components are generally not quite as critical as the geomembrane.

There will probably be little need to consider in-plant mill inspections but mill certificates should still be required. It is most important that textiles and net be transported with each roll having its own individual cover since the textile must not be allowed to get wet and the net must not become dirty. The textile must remain covered during storage since it will not be resistant to ultraviolet radiation.

Nets and textiles should be firmly keyed into the anchor trench and rolls must be oriented vertically on side slopes. There should be no joints in textiles and nets running along the side slopes. Overlaps must be adequate and geotextile stitching must be done with the correct thread. Nets must be tied together, preferably with plastic ties.

When geonet is deployed it must be followed immediately by geotextile or geomembrane to protect the geonet from ingress of dirt. The geotextile, in turn, should not remain exposed for more than 72 hours.

AS-BUILT DRAWINGS

A detailed set of as-built drawings should be prepared identifying panel and seam numbers, the location of cut-out test samples, repaired defects and seams and the location of any test coupons which have been installed for periodic monitoring of the membrane performance throughout its service life.

CONCLUSIONS

The guidelines for a thorough Quality Assurance program for the High Density Polyethylene geomembrane component of a hazardous waste containment system have been presented. A checklist of items which constitute the program is attached as Appendix A.

The principles of the program are applicable to other geomembrane materials used in similar installations and should be applied in conjunction with the information presented in National Sanitation Foundation Standard #54.

Components of the program may be extracted and used for quality assurance, control or vertification programs for less critical installations.

The program attempts to show that geosynthetic materials should be considered to be 'high tech' materials and while they can behave in undesirable ways, with due care, they can provide the long term containment services for which they are being designed.

It should be remembered that geomembranes are not 'impermeable' but that they just have very low permeability values. Because of this and the practical difficulty of installing systems with absolutely no leaks the wise designer will design his system such that a leak is not a major problem. If the optimum design is installed by a reputable installer and the whole project coordinated by a knowledgeable QA contractor the installation will provide the intended service.

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APPENDIX A

GEOMEMBRANE QUALITY ASSURANCE

CHECKLIST

DESIGN:

Chemical compatibility		[ ]
Thickness - subgrade, cover, load, ice, waves		[ ]
Seam geometry	- ice	[ ]
Geotextile	- gas venting, cushion	[ ]
	- filtration, drainage	[ ]
	- orientation, joining	[ ]
Drainage	- geotextile filter	[ ]
	- geonet	[ ]
	- orientation, joining	[ ]
	- number of layers	[ ]
Dewatering sump		[ ]
friction factors	- membrane, textile, net	[ ]
	- cover	[ ]
Geomembrane orientation	- minimize stresses	[ ]
	- minimize seams	[ ]
Anchor trench profile		[ ]
Penetrations		[ ]
Wear panels		[ ]
Safety lines		[ ]

MATERIAL SPECIFICATIONS:

NSF standard	[ ]
Manufacturers specifications	[ ]
Rework material	[ ]
Welding resin	[ ]

PROPOSAL INFORMATION:

Geomembrane specifications	- values	[ ]
	- test methods	[ ]
QC certificate samples		[ ]
Panel layout		[ ]
Welding equipment	- number of machines	[ ]
	- spare parts	[ ]
Previous project list		[ ]
Warranties		[ ]
Field QC program	- tests	[ ]
	- equipment	[ ]
	- criteria	[ ]
Ambient welding conditions		[ ]

CERTIFICATION:

Base resin (supplier)	[ ]
Audit tests on resin	[ ]
Geomembrane properties	[ ]
Product identification	[ ]
Loading report	[ ]

INSTALLATION QA:

Delivery inspection		[ ]
Audit tests		[ ]
Site storage	- flat surface	[ ]
	- rolls covered	[ ]
Weld qualification	- peel, shear	[ ]
	- microstructure	[ ]
Pre-installation meeting	- subgrade	[ ]
	- penetrations	[ ]
	- sump	[ ]
	- anchor trench	[ ]
Welder qualification	- daily	[ ]
Seam identification		[ ]
Contraction allowance		[ ]
Cut-out samples		[ ]
Seams to edge of liner		[ ]
Nondestructive testing	- visual	[ ]
	- vacuum box	[ ]
	- air pressure	[ ]
	- ultrasonics	[ ]
Daily reports		[ ]
Repairs		[ ]
Final walk-over		[ ]

DOCUMENTATION:

Final report	- daily reports	[ ]
	- test results	[ ]
	- repairs complete	[ ]
As-built drawing	- seams and panels numbered	[ ]
	- repair locations	[ ]
	- sample locations	[ ]

CERTIFICATION:

Base paper (supplier)
[illegible]
[illegible] properties
[illegible] specifications
Roofing paper

INSTALLATION QC:

Delivery inspection
Roof deck
Hot mopping - flat surface
- edge covered
Vent positioning - pool, sheet
- [illegible]
Pre-installation [illegible] - [illegible]
- [illegible]
- [illegible]
- [illegible]
Roller qualification - daily
[illegible]
[illegible]
[illegible]
[illegible] of [illegible]
[illegible] - [illegible]
- [illegible]
- air pressure
- ultrasonic
Daily reports
Airtest
[illegible]

DOCUMENTATION:

Final report - daily reports
- test results
- [illegible]
[illegible] - [illegible]
- [illegible]
- [illegible]